Interpreting the past, providing for the future

# Relationships Between Injection and Disposal Well Activities and Known Earthquakes in Wyoming, from 1984 to 2013

By Martin C. Larsen and Seth J. Wittke

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# RELATIONSHIPS BETWEEN INJECTION AND DISPOSAL WELL ACTIVITIES AND KNOWN EARTHQUAKES IN WYOMING, FROM 1984 TO 2013

**By Martin C. Larsen and Seth J. Wittke**

## INTRODUCTION

Public and scientific interest in the potential for induced seismicity in portions of the United States has been growing over the last few years. In response, the Wyoming State Geological Survey (WSGS) has conducted a review of existing data to quantify the potential relationship between earthquakes and injection and disposal well activity in Wyoming, from 1984 to 2013. This time period contains the best and most reliable earthquake reporting information available for Wyoming. Upon the evaluation of the entire state, the WSGS identified six sites that warranted further interpretation for potential induced seismicity.

Results from the review of the six sites concluded that in five of the sites the earthquakes that occurred were most likely the result of natural causes and unrelated to injection or disposal well activities. The remaining site, near Bairoil, Wyoming (Site C), showed no definitive correlation between injection well activity and seismic events. Further research may be necessary at Site C to determine if some induced seismicity has occurred, or if the seismic events were simply natural phenomenon that occur in a seismically active area. These six sites are discussed in greater detail in this report.

As part of the agency's ongoing responsibilities in the area of geologic hazards, the WSGS continually monitors earthquake activity across the state. In the future, if the agency notes an area with a sudden increase in seismic activity and/or a significant seismic event in the vicinity of active injection or disposal wells, the WSGS will report it to the Wyoming Oil and Gas Commission (WOGCC) and Wyoming Department of Environmental Quality (WDEQ). Further investigations would then be carried out to determine if induced seismicity is a possible cause of the earthquake(s).

## BACKGROUND

Earthquake activity can be triggered by a number of sources. Volcanic activity, landslides, and movement along a fault are examples of natural causes of earthquakes. In rare instances, anthropogenic (human) influences can also cause an earthquake; these events are referred to as "induced seismicity." Induced seismicity can potentially be triggered by a variety of industry related activities, including construction, geothermal energy production, mine subsidence and blasts, oil and gas field depletions, fluid injection for secondary and enhanced oil recovery, waste-water/fluid disposal, groundwater extraction, large water reservoir impoundment, drop forging, and military actions (conventional bombs and underground nuclear testing).

Given the recent national attention and focus on fracking in the United States, it is important to note that tens of thousands of wells have been fracked over the decades in Wyoming. To date the WSGS has observed no correlation between earthquakes and fracking operations. Some short-term micro-seismicity (below human detection) does occur in the Earth during a fracking operation, but does not represent what has become known as induced seismicity.

Induced seismicity generated by mining subsidence has been studied by industry and state and federal agencies. These events are often associated with mine workings and operations. Earthquakes generated from mine collapse range from magnitude 1.6 to 5.6 (Davies and others, 2013) with the vast majority occurring at the low end of the observed magnitude range. Examples of some of the relatively rare larger earthquakes related to mining in Wyoming include a 1995 partial ceiling collapse at the Solvay Chemicals trona mine in Wyoming that generated a

5.1 magnitude earthquake and a coal mine blast in 2012 at Cloud Peak Energy's Cordero Rojo Mine that caused a magnitude 4.5 earthquake.

In cases of oil and gas field depletion, the flexure of overburden units generates shear stresses that, on rare occasions, can induce slip along a weak shale layer (Hamilton and others, 1992). At the Lacq natural gas field in southwest France, more than 1,640 earthquakes were detected ranging from magnitude 1.9 to 6.0 due to gas depletion (Bardainne and others, 2008).

It has also been recognized that fluid injection within the subsurface can occasionally generate earthquakes. One of the most notable induced seismic incidents in the Rocky Mountain Region happened in 1967, a magnitude 5.3 earthquake occurred near Denver, Colorado, as a result of military waste fluid that was injected into a deep borehole at the Rocky Mountain Arsenal, a U.S. chemical weapons manufacturing center (Hsieh and Bredehoeft, 1981). Once the cause of the earthquake was identified pumping ceased at the arsenal and the earthquakes subsided.

For many years fluids have been injected (secondary and enhanced oil recovery methods) into oil and natural gas fields to optimize recovery. This is primarily done through water and carbon dioxide ($CO_2$) floods. At the Snipe Lake oil field in Alberta, Canada a 5.1 magnitude earthquake occurred in 1970; the earthquake was associated with the extraction of hydrocarbons using secondary recovery methods (fluid injection). Studies have indicated that these procedures may infrequently cause earthquakes ranging from magnitude 1.9 to 5.1 (Davies and others, 2013), with the majority of the earthquakes occurring at the low end of the observed magnitude range.

Fluid injection into the subsurface is a common procedure around the world and has been so for many decades by governments, municipalities, and various industries. This process is done to dispose of wastewater or chemicals below a serviceable water aquifer and to assist in the extraction of hydrocarbons located in oil and gas reservoirs. Other parameters that can contribute to induced seismicity related to fluid injection include the temperature and volume of the fluid injected, injection rates and pressure, proximity to faults, geologic formation targets, and the injection depth (Davies and others, 2013).

Over the last few years, there has been an increased interest in induced seismic events that may be related to injection/disposal wells. This has primarily been in Oklahoma, Texas, Arkansas, Colorado, New Mexico, and Ohio where recent earthquake activity potentially related to injection/disposal wells has occurred. These states are currently investigating the possible correlation between earthquakes and injection/disposal operations with industry, U.S. Geological Survey (USGS), and the U.S. Environmental Protection Agency (EPA). Induced seismic events in these and other cases appear to have some or many of the following general characteristics and observations:

- Associated with some "higher volume" injection/disposal wells (injecting hundreds or thousands of barrels per day); injecting fluids into "deep" (thousands of feet below the surface) rock formations.
- Associated with wells that require pumping (pressure) to dispose of the fluids versus wells that take fluid by means of gravity only.
- An area immediately around the well (within a few miles) suddenly experiences many small earthquakes (swarms/clusters) that are below magnitude 2. A few earthquakes of up to magnitude 5 have also been reported.
- Appear to be associated with fluid injection into relatively competent rock formations (well consolidated) and/or in formations that are relatively near basement rock (within a few thousand feet).
- Geologic faults exist in relative proximity to the well bore (within approximately 0 to 5 miles). The faults do not typically extend to the surface and are not recently active (Holocene aged, approximately 12,000 years to the present).
- Appear not to be related to wells undergoing active drilling operations.

## WELL AND EARTHQUAKE DATA

For this study, epicenters near injection and disposal wells in Wyoming were selected for the years 1984 to 2013. The data acquired for this study also include Class I, II, and V wells that are associated with fluid injection and disposal during the same time period. This time frame was chosen because it includes the most accurate and complete data available. Descriptions of Class I, II, and V wells are as follows:

The Wyoming Department of Environmental Quality (WDEQ) defines Class I injection wells as "deep disposal of industrial, commercial or municipal waste below the deepest usable aquifer" and includes all wells, which dispose of waste on a commercial basis, even if the waste would otherwise be injected into a Class II well. The agency responsible is the WDEQ Water Quality Division, Underground Injection Control (UIC) Program. Class II wells are defined as "deep disposal of hydrocarbons, brines, or other fluids associated with oil and gas production." The Wyoming Oil and Gas Conservation Commission (WOGCC) has primacy for Class II wells in the state of Wyoming. WDEQ defines Class V wells as "all other facilities not included in Classes I-IV which dispose of fluids into the subsurface, including coal bed methane (CBM) produced water and large capacity septic systems." The agency responsible is the WDEQ Water Quality Division, UIC Program.

The WDEQ protects Wyoming's groundwater resources by regulating the disposal of brine and other wastes produced from drilling production as well as the disposal of waste on a commercial basis. The UIC Program, implemented by WDEQ, regulates the injection of waste fluids into the subsurface to protect current and future uses of underground sources of drinking water. WDEQ, implemented by the EPA, regulates Class I, II, III, IV, and V UIC facilities.

The WOGCC has primacy on Class II wells and maintains a catalog on the activity occurring at each well. Information on active and inactive injection and disposal wells (Class II) includes dates, quantities of fluid, pressure, and targeted geologic formations or units and can be accessed through the WOGCC database system.

The WSGS maintains a database of earthquake events and receives near real-time notices from the USGS on all reported seismic events that take place in Wyoming. The agency's Wyoming Earthquake Database Internet Map Service (IMS) (http://ims.wsgs.uwyo.edu/earthquakes/) is updated on a weekly basis to reflect present and historic seismic activity throughout the state. Earthquake data are acquired from the USGS' Advanced National Seismic System (ANSS) Composite Earthquake Catalog. The catalog includes compiled event information from many seismic networks in the country and worldwide. As a compilation of seismic networks, the ANSS is not uniform in its coverage and some seismic networks are more accurate than others.

Outside of the Yellowstone and Grand Teton National Park area there is only one seismic station (Pinedale Array Site 31) in Wyoming monitored by the USGS. There are three stations just outside the state in Idaho, Montana, and South Dakota. This limits the location accuracy of earthquake epicenters and depths (foci). With the limited seismic station coverage in Wyoming and surrounding states, it can be extremely difficult to determine the true depths of the earthquake focus. Some of the depths taken directly from the ANSS catalog were assigned a 5 km depth by the USGS because the actual solution depths could not be accurately determined. USGS had no valid depth control with the location program that they were using at the time and arbitrarily held the depths to 5 km. The USGS indicated the true depth of these 5 km events could be anywhere within the Earth's upper crust, 0 to 20 km below the Earth's surface (Bruce Presgrave, personal communication, U.S. Geological Survey).

## METHODS

ANSS earthquake data and WOGCC and DEQ injection and disposal well information from 1984 to 2013 were used for this study. Well data acquired from WOGCC did not undergo a quality control process. Earthquake events are recorded by variable seismic stations, which can affect location and depth certainty. Some earthquakes are located with better precision than others. This report is based on data that existed at the time this study was performed.

The data were divided into three periods (by decade), Time Period 1: 1984-1993, Time Period 2: 1994-2003, and Time Period 3: 2004-2013. Each period contains the earthquake and injection and disposal well activity that occurred during that time. Initially, a 50 km buffer was established around each injection well. Earthquakes located within the 50 km buffer were queried out and used for further analysis. The purpose of this approach was to eliminate all earthquake activity not in proximity to injection or disposal wells, to determine if any seismic patterns existed, and account for any uncertainty in the location of seismic epicenters. A second buffer of 5 km was then applied around each earthquake epicenter. The 5 km buffer was established by Davis and Frohlich (1993) as part of their protocol for induced seismicity criteria and is based on the geographical and geological relationship between the sites of injection and seismic activity. Areas where earthquake locations were greater than 10 km below local injection/disposal wells or reported on or near the surface, were not considered for further study. Wells that fell within the 5 km buffer were used for more focused analysis and broken out into individual sites in each period (Time Period 1: 1984-1993, Time Period 2: 1994-2003, and Time Period 3: 2004-2013). Injection data for select wells within each site were examined where wells were proximal to the recorded earthquakes.

Earthquake epicenter and focus, location and depth of the injection and disposal wells, fluid disposal history (injection timing), and selected geologic formations were then uploaded into Petra, computer software for creating subsurface models. Formation tops were picked automatically by modeling software (Petra).

Computer 3D-models representing the depths of the injection and disposal wells and the earthquake focus were then generated using the compiled data. Kelly bushing elevations, acquired from WOGCC well logs, were used to generate a generalized ground surface. Wells were then projected into the subsurface based on reported depth from the kelly bushing elevation. Formation tops were also taken from WOGCC well logs and displayed in the subsurface to approximate the regional structure. The selected formation tops for each site were based on the reported information taken from the well logs. The selected formations were used to depict the general structure of the formations and, if available, the lowest formation and/or the targeted formation for disposal. Other formation tops were selected to illustrate the general subsurface geology and to approximate any major structural features or faults that may act as potential earthquake zones.

Plates 1a, 2a, and 3a represent the locations of the injection and disposal wells and epicenters that were active for each period. Injection and disposal wells are displayed based on reported depth. Earthquakes use the same color as the wells to reflect depth; additionally, the size of the earthquake symbol represents the magnitude of the earthquake.

Plates 1b, 2b, and 3b show the sites that were identified for each period. Each site is represented by two figures. Figure A shows the location of the injection and disposal wells in relation to the epicenter in map space. Figure B depicts the depths of the injection and disposal wells, the determined depth of the earthquake (focus), and the tops of selected geologic formations and/or units via the 3D model. Sites that appeared to have some geographic correlation with injection and seismic activities were further investigated. The site figures show potential areal linkage based on the proximity of the activities (seismic and injection), injection depths in relation to the foci (depths), and the targeted formations for waste disposal. Using the WOGCC database and the ANSS catalog, the timing of earthquakes and waste fluid injection were compared to determine if there were any temporal correlations.

With the help of FEMA Region VIII, WSGS conducted an earthquake scenario at Site C based on a magnitude 5.3 event using FEMA's HAZUS-MH software platform (FEMA, 2014). The scenario was completed in order to approximate potential losses related to a “worst case scenario” earthquake based on a maximum magnitude of 5.3 (Davies and others, 2013). The scenario was modeled as a magnitude 5.3 earthquake at a depth of 2 km, located in the middle of the existing injection field at Site C. 2002 Census data, including population, buildings, and infrastructure were used to calculate loss estimations.

## FINDINGS

### Time Period 1: 1984-1993 (Plates 1a and 1b)

The 1984-1993 time period includes 3,901 WOGCC Class II injection wells, 52 WOGCC Class II disposal wells, and 11 Class I WDEQ injection wells (pl. 1a). The initial search criteria (50 km buffer, ≥ 2.0 magnitude) identified 52 earthquakes in Time Period 1. Based on the 5 km buffer criteria, three sites were identified (Sites A, B, and C) with a total of three earthquakes.

*Site A (Sublette and Lincoln Counties)*

Site A consists of 15 WOGCC Class II injection wells, four WOGCC Class II disposal wells, and a magnitude 3.0 earthquake that occurred on September 4, 1993. Map view (pl. 1b) shows the location of the injection and disposal wells (API #) in relation to the epicenter. The 3D-model illustrates a subsurface view showing the depths of the 19 wells, the location of the focus, and the tops of the Almy and Mesaverde formations (pl. 1b). The reported depth of the focus is 0.7 km (2,297 ft), the deepest injection well is 0.77 km (2,530 ft), and the deepest disposal well is 0.31 km (1,015 ft).

Four disposal and six injection wells were active approximately 2 to 12 years before the seismic event on September 4, 1993 occurred at Site A. The injection depth of well API 49-035-05164, located 0.72 km northeast of the epicenter, is approximately at the same depth of the epicenter. The other active wells are located 2.8 km west-southwest of the epicenter, and the injection depths were much shallower than the epicenter. Well API 49-035-05164 is in the vicinity of the epicenter and the injection depth is approximately at the same estimated depth. However, it should be noted that there is a great deal of uncertainty associated with the actual depth of the epicenter. The amount of fluids that were injected increased during the year 1997 with no associated earthquake activity. The amount of fluid injected into the well decreased in 1998, but ongoing disposal activities continue to occur with no associated earthquake activity. Given that this was a single seismic event and injection has occurred for decades, the best interpretation that fits the current seismic and well data is that the seismic event that took place on September 4, 1993 was coincidental and the result of natural causes.

*Site B (Fremont County)*

Site B consists of two WOGCC Class II injection wells and a magnitude 4.0 earthquake that occurred on October 10, 1992. Map view (pl. 1b) shows the location of the injection wells (API #) in relation to the epicenter. The 3D-model illustrates a subsurface view showing the depths of the two wells, the location of the focus, and the tops of the Muddy Sandstone, Tensleep Sandstone, and Gallatin Limestone (pl. 1b). The reported depth of the earthquake focus is 5 km (16,404 ft) and the deepest injection well is 3.5 km (11,458 ft).

Although an earthquake occurred at Site B in 1992, there were spans of similar injection activities during 1994 to 2013 in the same area that did not result in a nearby earthquake, or increased earthquake activity. Based on the available data, the seismic event that occurred at Site B was most likely the result of natural causes and unrelated to injection well activities.

*Site C (Fremont, Carbon, and Sweetwater Counties)*

Site C, in Time Period 1, consists of 151 WOGCC Class II injection wells and a magnitude 3.8 earthquake that occurred on June 1, 1993. Map view (pl. 1b) shows the location of the injection wells (API #) in relation to the epicenter. The 3D-model illustrates a subsurface view showing the depths of the 151 wells, the location of the focus, and the tops of the Muddy Sandstone and Tensleep Sandstone (pl. 1b). The reported depth of the earthquake is 5 km (16,404 ft) and the deepest injection well is 2.5 km (8,200 ft).

Site C is discussed in greater detail below (pg. 8).

**Time Period 2: 1994-2003 (Plates 2a and 2b)**

The 1994-2003 time period includes 3,242 WOGCC Class II injection wells, 251 WOGCC Class II disposal wells, and 80 Class I and V WDEQ injection wells (pl. 2a). The initial search criteria (50-km buffer, ≥ 2.0 magnitude) produced 45 earthquakes between 1994 and 2003. Based on the 5-km buffer criteria, two sites were identified (Sites C and D) with a total of four earthquakes.

*Site C (Fremont, Carbon and Sweetwater Counties)*

Site C, in Time Period 2, consists of 156 WOGCC Class II injection wells, a magnitude 4.0 earthquake that occurred on May 26, 2000 and a magnitude 3.2 on May 30, 2000. Map view (pl. 2b) shows the location of the injection wells (API #) in relation to the epicenter. The 3D-model illustrates a subsurface view showing the depths of the 156 wells, the location of the focus, and the tops of the Dakota Formation and Tensleep Sandstone (pl. 2b). The reported depth of the earthquakes is 5 km (16,404 ft) and the deepest injection well is 2.7 km (8,860 ft). Site C is discussed in greater detail below (pg. 8).

*Site D (Natrona County)*

Site D consists of 14 WOGCC Class II injection wells, a magnitude 4.2 earthquake that occurred on October 19, 1996 and a magnitude 3.7 on February 1, 2003. Map view (pl. 2b) shows the location of the injection wells (API #) in relation to the epicenter. The 3D-model illustrates a subsurface view showing the depths of the 14 wells, the location of the foci, and the tops of the Parkman Sandstone and the Dakota Formation (pl. 2b). The reported depths of both earthquakes (foci) are 5 km (16,404 ft) and the deepest injection well is 2.3 km (7,540 ft).

Although earthquakes occurred in 1996 and 2003 at Site D, there were other similar spans of injection activities and operations from 1994 to 2013 in the same areas that did not result in additional or increased earthquake activity. Based on the available data, the seismic events that occurred at Site D were most likely the result of natural causes and unrelated to injection well activities.

**Time Period 3: 2004-2013 (Plates 3a and 3b)**

The 2004-2013 time period includes 3,435 WOGCC Class II injection wells, 355 WOGCC Class II disposal wells, and 436 Class I and V WDEQ injection wells (pl. 3a). Applying the 50 km buffer and a 2.0 magnitude or greater for the earthquakes, 88 earthquakes were identified. Based on the 5 km buffer criteria, three sites were identified (Sites C, E, and F) with a total of five earthquakes.

*Site C (Fremont, Carbon and Sweetwater Counties)*

Site C, in Time Period 3, consists of 151 WOGCC Class II injection wells and magnitude 3.1 and 3.5 earthquakes that occurred on December 25, 2005 and November 11, 2010. Map view (pl. 3b) shows the location of the injection wells (API #) in relation to the epicenters. The 3D-model illustrates a subsurface view showing the depths of the 151 wells, the location of the focus, and the tops of the Nugget Sandstone and Tensleep Sandstone (pl. 3b). The reported depths of the earthquakes are 5 km (16,404 ft) and the deepest injection well is 2.5 km (8,200 ft).

Site C is discussed in greater detail below (pg. 8).

*Site E (Campbell County)*

Site E consists of two WOGCC Class II injection wells, a magnitude 3.3 earthquake that occurred on January

27, 2011 at a depth of 8.8 km (21,872 ft), and a magnitude 2.5 earthquake that occurred on May 10, 2013 at a reported depth of 5 km (16,404 ft). Map view (pl. 3b) shows the location of the injection wells (API #) in relation to the epicenters. The 3D-model illustrates a subsurface view showing the depths of the two wells, the location of the earthquakes, and the tops of the Sussex Sandstone and the Minnelusa Formation (pl. 3b). The deepest injection well is 3.7 km (12,153 ft).

Injection well operations began 10 to 20 years before the two seismic events took place in Site E. Well API 49-005-26062 commenced injection activities in 1994 and well API 49-005-30942 began injection operations in 2003. Based on the data, there is no direct correlation with fluid disposal activity and the seismic events. The seismic events are likely the result natural causes.

*Site F (Weston County)*

Site F consists of seven WOGCC Class II injection wells and a magnitude 2.7 earthquake that occurred on May 2, 2006. Map view (pl. 3b) shows the location of the injection wells (API #) in relation to the epicenter. The 3D-model illustrates a subsurface view showing the depths of the seven wells, the location of the focus, and the tops of the Lewis Shale, Niobrara Formation, and Dakota Formation (pl. 3b). The reported depth of the earthquake is 0.8 km (2,625 ft) and the deepest injection well is 2.4 km (7,842 ft).

Although injection activities occurred at Site F during Time Period 3, no injection operations occurred during 2005 or 2006 when the earthquake took place. Because no injection operations occurred immediately before or during the seismic event, the most plausible interpretation is that the single seismic event at Site F was the result of natural causes and unrelated to injection well activities.

**Site C Discussion (all Time Periods)**

Unlike the other sites that were evaluated, Site C has experienced earthquakes and injection activity over all three time periods (from 1984-2013) making Site C unique and worthy of a more in-depth evaluation.

Multiple injection wells at Site C, ranging from 151 to 156 wells, have had waste fluid or $CO_2$ injection operations from 1984 to 2013 (Time Periods 1, 2, and 3). Many of these wells have undergone $CO_2$ and water injection into the Tensleep and/or Madison formations.

Array Network Facility (ANF) data were added to Site C in Time Period 3 (pl. 3b). EarthScope's ANF recorded all seismic events in Wyoming from 2006-2011 through the USArray project. The project recorded mine blasts and other anthropogenic seismic events as well as natural events but did not differentiate between the two. Magnitudes were not calculated for ANF data, although it can be assumed that events that do not appear on the ANSS Composite Earthquake Catalog have magnitudes less than 2.3. Seven seismic events were detected by ANF at Site C in Time Period 3 that ranged from 0 to approximately 14 km in depth (Plate 3b). Seismic events ANF-3 and ANF-5 were located at 0 km suggesting anthropogenic activities occurring at or near the ground surface or poorly calculated event locations. Seismic events ANF-1, ANF-4, and ANF-7 were not added to the 3D model for display purposes. The foci depths, 8.6, 12.7, and 14.2 km respectively, were significantly greater than the deepest injection well (2.7 km) and the deepest targeted formation top (Tensleep Sandstone) ranging from 2.2 to 2.5 km. Seismic event ANF-7 occurred at 14.2 km and was shortly followed by seismic event ANF-6, at a depth of 2.8 km. However, there is not enough data to confirm or refute the two events are related.

Two Quaternary fault systems are located within the vicinity of Site C. The South Granite Mountains fault system; approximately 13 km north of Site C, is a 125 km long west-northwest trending, north dipping fault system that is comprised of five major sections (Crooks Mountain, Ferris Mountains, Green Mountains, Muddy Gap, and Seminoe Mountains). Paleoseismic investigations were conducted at the Ferris and Green Mountains sections. A maximum surface-faulting event of 1-1.5 m displacement was determined on the Ferris Mountains section. The trench at the Green Mountains section did not reveal any direct evidence for timing and amount of displacement.

The Chicken Springs fault system, approximately 16 km southwest of Site C, is a group of disrupted fault segments trending west-northwest over 13 km in length. No paleoseismic studies have been conducted on the Chicken Springs faults. The true impact of these Quaternary faults to the seismic events observed in Site C is not known at this time. However, the existence of these faults does point to the potential for natural elevated local seismicity in the Site C area.

Subsurface structures (faults, anticlines, and synclines) have been interpreted for the Lost Soldier and Wertz oil fields in Site C. Figure 1 shows the location of 1984-2013 injection wells, the ANSS earthquakes that occurred from 1984 to 2013, ANF seismic event locations, the locations of the interpreted subsurface faults, and cross-section line N-N' (Blackstone, 1991). The basemap is a structure contour map of the Precambrian basement for the southeastern Wind River Range, southwestern Sweetwater Uplift, and the Rawlins Uplift area that was scanned and

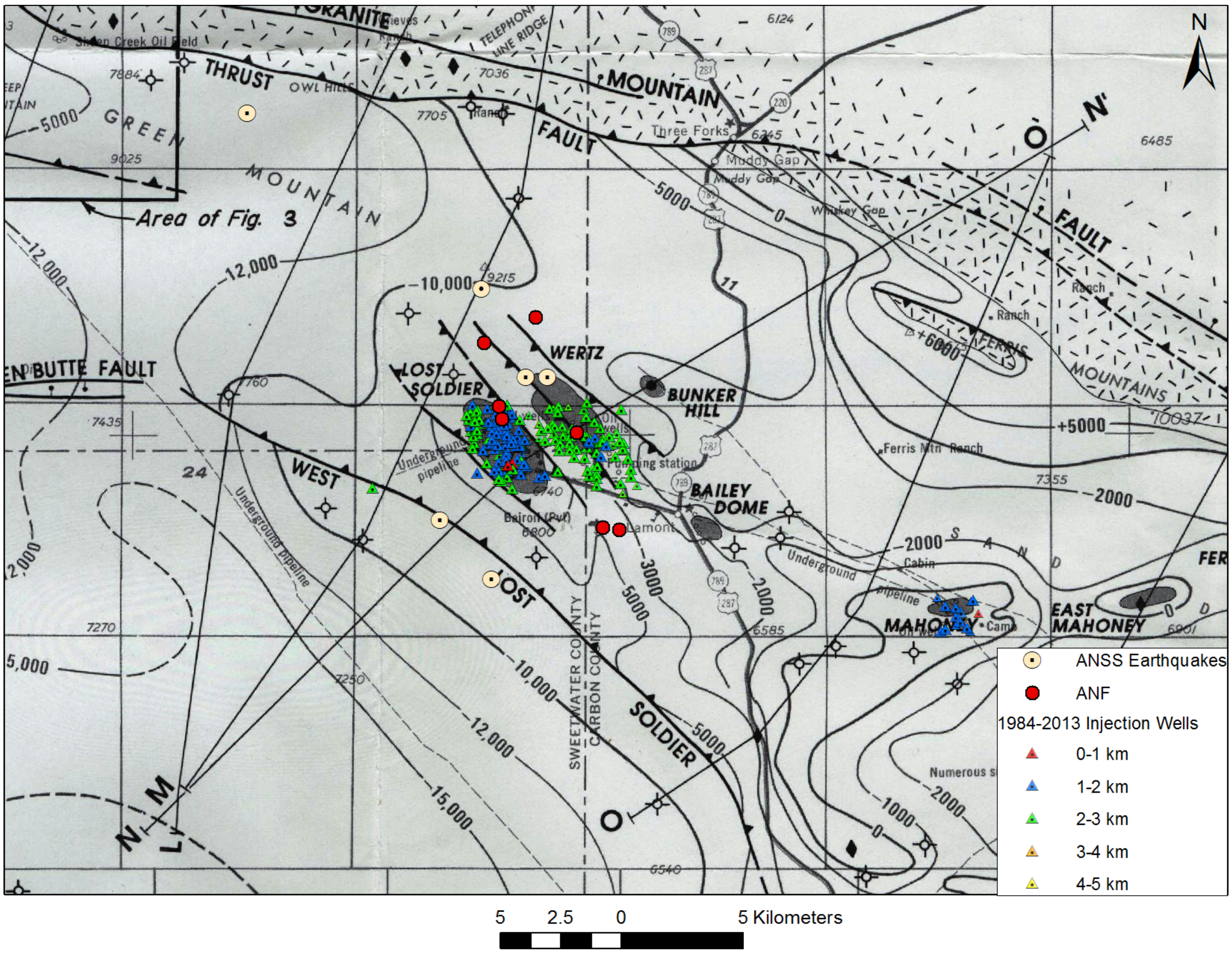


**Figure 1.** Structure contour map showing the location of the earthquakes that occurred at AOI C from 1984 to 2013, ANF seismic event locations, 1984 to 2013 injection well locations, the Lost Soldier and Wertz oil fields, and fault systems.

cropped out for Site C (Blackstone, 1991).

The largest producing oil fields in this area are in the Lost Soldier and Wertz anticlines. Cross-section line N-N' illustrates potential subsurface structures (faults) that may act as points of weakness to trigger deep seismicity from wastewater injection operations (fig. 2). The major fold complex and faults trend to the northwest. The folds are fault bounded to the southwest by the West Lost Soldier fault. The West Lost Soldier fault, a major reverse fault, is projected into the Precambrian basement and becomes listric with depth. Faults northeast of the West Lost Soldier

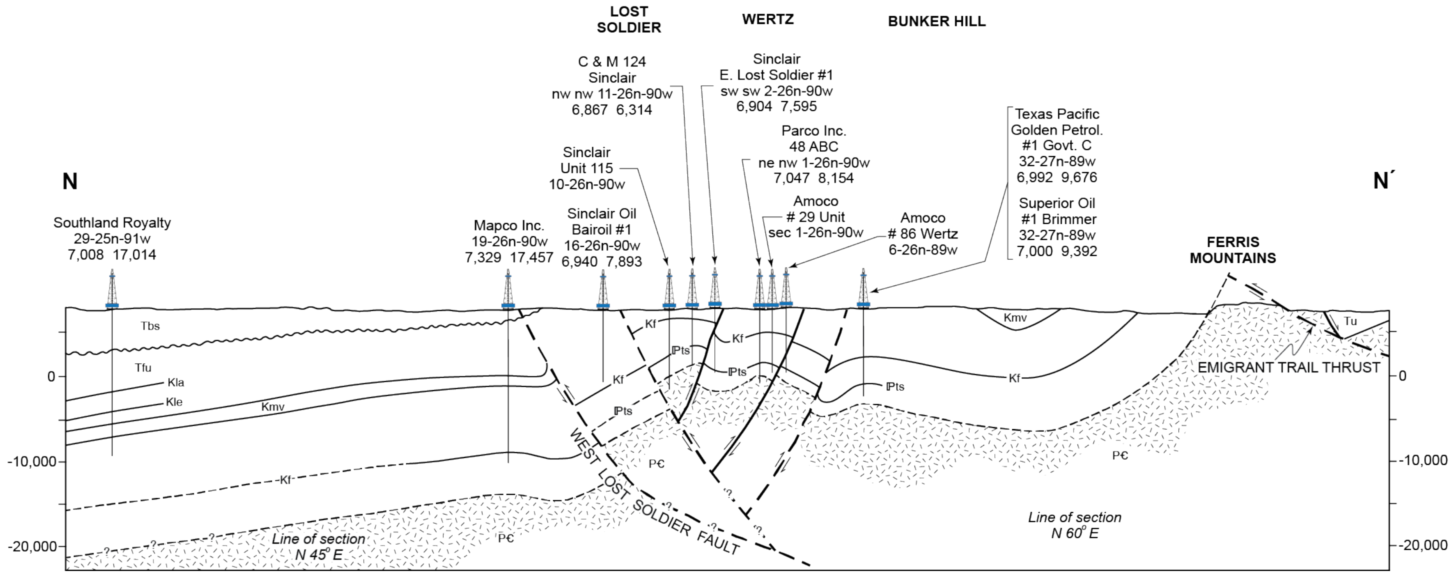


**Figure 2.** Geologic cross section, N-N’, across the Lost Soldier and Wertz anticlines illustrating the geologic units, oil well depths, and subsurface structures (faults, anticlines, and synclines). The West Lost Soldier reverse fault is projected into the Precambrian basement and becomes listric with depth. Faults to the northeast of the West Lost Soldier fault were interrupted by well log data (Blackstone, 1991).

fault were interrupted from well log data.

From 1984 to 2013 five notable seismic events, 2.5 magnitude to 4.0, have occurred at Site C. It is important to note that none of these events were preceded or followed by detectable earthquake swarms/clusters. At Site C during Time Period 2 (pl. 2b) a magnitude 4.0 occurred on May 26, 2000. Four days later, on May 30, 2000, a magnitude 3.2 earthquake happened. Earthquake swarms/clusters associated with induced seismic events potentially related to wastewater injection activities have been recorded in Arkansas, Ohio, and Oklahoma (Davis and Frohlich, 1993, Horton, 2012, Nicholas J. van der Elst and others, 2013, and Karanen and others, 2014). Similar types of earthquake swarms/clusters have not been recorded or observed at Site C.

The ANSS and ANF seismic data show a total of 12 seismic events have occurred from 1983 to 2013 at Site C, illustrating that this is a seismically active area. The vast majority of these events were relativity small in magnitude and there have been no earthquake swarms/clusters recorded with any event. Based on the lack of detailed subsurface data available to the WSGS, limited seismic station coverage, and poorly calculated epicenters with no depth control on the ANSS foci, it was not possible to perform a detailed and complete evaluation of the area. However, while we [the authors] can definitely conclude that this seismically active area is in close proximity to well injection operations, we cannot determine if there is any direct correlation with injection well operations and the seismic events in this area, or if the seismic events were simply natural phenomenon.

## SEISMIC LOSS POTENTIAL

As mentioned above, this report illustrates that Site C is seismically active. With this knowledge the WSGS requested FEMA Region VIII to perform a seismic loss potential run. It is common to have such runs made in active seismic regions in the United States, in areas with naturally occurring earthquakes, and areas with potentially induced seismicity.

Peak Ground Accelerations (PGAs) calculated within Site C range from 10%g (gravity) to 32%g. PGA within the town of Bairoil is projected to be 29-32%g. This range of acceleration would produce very strong perceived ground motions by residents. Based solely on PGA, damage would likely be negligible in buildings of good design and construction. Damage may be greater in buildings of poor construction. Unstable objects may be moved or overturned; dishes, windows, and chimneys may be broken (Wald and others, 2006).

The model shows minimal loss estimations for the proposed 5.3 magnitude earthquake. No injuries are anticipated in the modeled event. There is no projected damage to buildings, emergency facilities, or transportation routes. The scenario calculated one oil pipeline leak in the study area, but no pipeline breakages. Modeled economic losses to utilities within the scenario equal $10,000. Although losses cannot be attributed to a specific utility, they are likely due to the pipeline leak. There are no other projected economic losses.

In summary, economic losses from a maximum magnitude event (magnitude 5.3) at Site C would be negligible. Damage would likely be restricted to unsecured items falling from shelves or walls. Injuries are not anticipated based on the scenario results. Perceived ground motions could be very strong; the town of Bairoil could experience ground motions between 29-32%g.

## FUTURE RESEARCH

The WSGS will continue to monitor earthquake activity across the state by incorporating ANSS data into the agency's Wyoming earthquake catalog IMS. If there are areas with high or unusual seismic activity and/or a significant event in the location of active injection and disposal wells, the WSGS will conduct an investigation. Selected injection operations, such as Site C, will be monitored to better understand the possible relationship between fluid disposal injection and disposal activities and seismicity in Wyoming. If in the future there are areas with high seismic activity and/or a significant seismic event in the vicinity of active injection or disposal wells, the WSGS will report it to the WOGCC and WDEQ and conduct a further investigation to determine if induced seismicity is a possibility.

We encourage the company or companies that operate injection and/or disposal wells in areas that have the potential for induced seismicity to investigate/evaluate the subsurface geology around the wells and monitor their operations in relation to seismicity. Tracking seismicity and operations in areas of injection/disposal wells can provide a better understanding of potential induced seismicity and if needed, the implementation of mitigation efforts.

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## GLOSSARY

**Anthropogenic:** Of, relating to, or resulting from the influence of human beings on nature.

**Earthquake swarms/clusters:** Seismic events where an area experiences a sequence of multiple earthquakes occurring over a short period.

**Epicenter:** Location on the Earth's surface that lies directly above the earthquake focus.

**Focus (pl, Foci):** Depth or point within the Earth where an earthquake fault begins to rupture. This is also referred to as the hypocenter.

**Fluid-Injection/disposal well:** A well that is used to dispose of water, brines, hydrocarbons, and other fluids associated with oil and gas production, industrial, commercial or municipal waste below the deepest useable aquifer.

**Induced seismicity:** Seismic events that are caused by human activity. This is also referred to as triggered seismicity.

**Kelly bushing elevation:** The distance from the rotary kelly bushing of the drilling rig to mean sea level.

**Mine workings:** A mine or quarry this is being or has been worked.

**Peak Ground Acceleration (PGA):** The largest ground acceleration experienced during a seismic event.

**Quaternary faults**: Faults that are recognized on the surface which show evidence of movement in the last 1.6 million years.